

Indirect reciprocity with costly information

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Goal

To study the evolutionary dynamics of indirect reciprocity based on reputation information when sharing and maintaining such information is costly.

Background and motivation

Humans are characterized as reciprocal animals cooperating with each other even though such behavior is costly. Why costly cooperation is frequently observed in many species, including humans, has been an evolutionary mystery, which is widely studied by using game theory. The Prisoner's Dilemma (PD) game and its variants are typically used for examining cooperative behavior in social dilemmas. In a PD game, players have a choice to cooperate or to defect: although mutual cooperation maximizes their social welfare, defection is always the dominant strategy. Therefore, additional mechanisms are required for stabilizing cooperation, such as repeated encounters or a structured population (e.g., Nowak 2006).

Indirect reciprocity is a particularly important mechanism for sustaining cooperation when individuals rarely interact with the same partners (Nowak and Sigmund 2005); such one-shot interactions are increasingly ubiquitous in human societies (e.g., anonymous encounters in online marketplaces such as amazon.com and ebay.com; Bolton et al. 2004). For indirect reciprocity, reputation information plays a key role (Alexander 1987). In a canonical model of reputation-based indirect reciprocity, individuals possess reputation scores determined by their past actions toward other individuals (Nowak and Sigmund 1998a, 1998b). Individuals helping others are regarded as good and those cheating are regarded as bad. Individuals help others when those have a good reputation, but not those when they have a bad reputation. Consequently, helping others to maintain a good reputation is more beneficial than cheating to gain a momentary profit. Recently, evidence for indirect reciprocity has been found in animals (Bshary and Grutter 2006; Akçay et al. 2010).

Sharing information about reputations is crucial for the mechanism of indirect reciprocity. In practice, however, it often is costly to share information about the reputations of individuals. For example, while amazon.com adopts a feedback mechanism to assess each seller, customers often do not submit such feedback, because for them this involves extra work. More in general, collecting, sharing, and maintaining information is costly, so the availability and quality of information may suffer from a tragedy of the commons (Hardin 1968; Ostrom 1990). Individuals, or a marketplace as a whole, may try to address these challenges by charging fees before allowing individuals to access reputation information, which can lead to the emergence of a reputation market operating alongside the dynamics of indirect reciprocity.

Most previous studies in biology have ignored the costs involved in sharing information about the reputation of individuals. In contrast, several studies in economics have treated the issue of costly observation (Ben-Porath 2003; Miyagawa et al. 2008). Most of them, however, only considered the case in which observing others and getting information about the reputation of those individuals is costly. In the present study, we will explore a general model in-

cluding two types of cost: costs for obtaining information and costs for exchanging information. Moreover, we will consider extensions in which individuals exchange reputation information, and may be motivated to contribute false or inaccurate information to others.

Research questions

In the present study, we will investigate the dynamics of indirect reciprocity based on costly reputation information. We will identify conditions for sustaining cooperation and examine the following specific aspects:

- Competition among reputation providers. In a population with pairwise interactions and communication, we consider many reputation providers. If the quality of information offered by a reputation provider is high, every reputation customer will be motivated to obtain information from this provider. We will thus explore competition among reputation providers and identify conditions for the emergence of hub providers.
- Modes of exchanging reputation information. Individuals can deal with reputations either through a centralized institution (e.g., the assessment system in amazon.com) or through pairwise communication (e.g., gossip). We will examine which of those two modes is more efficient.
- Deficient information. Several animals implement their systems of indirect reciprocity by direct observation (Bshary and Grutter 2006; Akçay et al. 2010). Humans, however, often adopt indirect observation, not the least since we can communicate with each other using complex language (Dunbar 1998; Nowak and Sigmund 2005; Sommerfeld et al. 2007). We will investigate conditions for cooperation when reputation may mistakenly spread via gossiping, or when reputation providers offer false or inaccurate information.

Methods and work plan

Model overview

We extend the canonical model of indirect reciprocity with binary reputations (Nowak and Sigmund 1998a, 1998b) in a population of M individuals. In this model, each individual as perceived by each other individual has a simple reputation: good (G), bad (B), or unknown (U). Specifically, each individual has its information storage represented by a vector of reputations of others. Each element of these vectors represents the relevant individual's reputation. Observing a game and exchanging the resultant information impose cost on individuals. Each individual who needs reputation information pays a cost when consulting a reputation provider.

Below, we first describe a multi-provider model as an individual-based model to be studied by numerical analysis. In this model, N denotes the number of existing reputation providers, so that $N = 1$ represents a monopolistic situation (recovering the canonical model of indirect reciprocity), while $N = 2$ represents a duopolistic situation. If N is large, there is competition among many reputation providers. We will successively analyze the one-provider and two-provider models, before addressing the general case of N providers. In particular, the one-provider and two-provider model can be studied by mean-field analysis. Model extensions for studying additional research questions are described at the end of this section.

Donation game

We consider a sufficiently large population, in which individuals encounter each other and play the so-called donation game. In a one-shot donation game, two individuals are selected uniformly randomly and participate in the game. One serves as a donor, and the other serves as a recipient, while N reputation providers serve as observers.

The donor either cooperates (C) with or defects (D) against the recipient. The donor makes a choice (C or D) according to its strategy (ALLC, ALLD, or DISC) and the recipient's reputation (G, B, or U). ALLC donors always cooperate, ALLD donors always defect, and DISC donors cooperate if the recipient's reputation is G or U (so-called trustful discriminators). The donor pays a cost c and the recipient gains a benefit b if the donor cooperates ($0 < c < b$), whereas the payoffs of the game are 0 if the donor defects.

Information exchange

Prior to deciding whether to cooperate or defect, a DISC donor requests the recipient's reputation from a reputation provider and pays a cost $\beta > 0$ to the provider. If the provider knows the recipient's reputation (G or B), the donor sticks to this provider after the game. Otherwise (U), the donor changes to a randomly chosen other provider after the game. Tolerances to a larger number of unsuccessful requests can be considered, and non-uniform distributions can be specified for choosing the new provider.

At the same time, all providers may observe the game. An observer i decides whether or not to do so according to its observation probability q_i . If the provider observes, it pays a cost $\gamma > 0$ and updates its reputation information concerning the donor. If the provider does not observe, the donor's reputation in the provider's information storage changes to U. Note that a donor never uses its own information storage for playing the donation game. In this way, we exclude effects of direct reciprocity.

Errors

We can introduce errors of implementation and/or perception, with donors choosing their actions mistakenly and/or observers failing to update their information storage correctly.

Assessment rule

The reputations of individuals are updated based on their past actions and the assessment rule used by the population. We consider second-order assessment rules that assign reputations G or B to donors depending on whether these donors used strategies C or D toward recipients and on whether these recipients had reputations G or B. We may explore various assessment rules such as so-called image scoring and simple standing.

Update rule

After sufficiently many games, we determine the average payoffs of all individuals (including the providers) and update their strategies accordingly. We assume that individual i adopts the strategy of individual j with probability $1/(1 + \exp(-s(P_j - P_i)))$, where P_i and P_j are the respective payoffs and $s > 0$ controls the intensity of selection.

Mean-field analyses

Here we describe the method of mean-field analysis for large populations ($M \gg 1$) with two providers ($N = 2$). In this case, we consider replicator dynamics based on the payoffs of the

different strategies in the donation games (ALLC, ALLD, and DISC) and competition between the two reputation providers. We denote the fractions of individuals using strategies ALLC, ALLD, and DISC by x_1 , x_2 , and x_3 , respectively, the fractions of individuals using these strategies and having a good reputation by g_1 , g_2 , and g_3 , respectively, the strategies of the two providers by q_1 and q_2 (with $q_1 > q_2$), and the fractions of individuals consulting each of the two providers by p_1 and p_2 (with $p_1 + p_2 = 1$).

For the purpose of this mean-field analysis, the strategies of the two providers are fixed ($q_1, q_2 = \text{const.}$), and we assume that reputations change and individuals switch providers sufficiently faster than strategies change ($\dot{g}_1, \dot{g}_2, \dot{g}_3, \dot{p}_1, \dot{p}_2 \gg \dot{x}_1, \dot{x}_2, \dot{x}_3$). After sufficiently many donation games, g_1 , g_2 , g_3 , p_1 , and p_2 thus equilibrate. On this basis, we can calculate the payoffs of ALLC, ALLD, and DISC, which we denote by P_i for $i=1,2,3$. Using these payoffs, we can examine the replicator dynamics $\dot{x}_i = x_i(P_i - \bar{P})$, for each strategy i , where $\bar{P} = \sum_i x_i P_i$ is the average payoff.

Provider distribution

In the multi-provider model, a reputation provider i has k_i customers. The emergence of hub providers can thus be investigated by studying the probability distribution of k_i through numerical analyses. If the distribution of k_i is non-Poissonian, this suggests that hub providers emerge. We will check, in particular, whether the distribution of k_i follows a power law, the characteristic of a scale-free distribution.

We will also check whether the number N of providers and the distribution of k_i converges to either of the following two extremes: $N = 1$ with $k_1 = M$, corresponding to a centralized institution with global information storage accesses by all individuals, or $N = M$ with $k_i = 1$, corresponding to pairwise communication among all individuals.

Deficient information

In a model by Nakamaru and Kawata (2004), individuals are checking the reliability of reputation information against their direct experiences, as a means of detecting deficient information. We will instead consider a model in which providers that contribute deficient information are detected by customers examining reputation information from multiple providers (Sommerfeld et al. 2008). We thus extend the basic multi-provider model through two modifications: (1) We allow providers, with a certain probability r_i , to avoid paying the cost β by providing reputation information not based on observation. Such providers evidently are unreliable. (2) Each donor asks a fraction f_i of providers about the recipient's reputation. The donor accepts the majority's opinion as the reputation of the recipient, and providers that contribute a minority opinion lose the donor as a customer.

Work plan

We will attempt to examine the three research questions listed above in the indicated order, and proceed as far as time permits.

Relevance and link to EEP's research plan

Indirect reciprocity is considered a main mechanism for the emergence and maintenance of cooperation, particularly in the human societies. This project, therefore, contributes to EEP's *Evolution of Cooperation* research project.

Expected output and publications

The results of this project are intended for publication as a coauthored article in an international scientific journal. M.N. also expects this work to be a part of his Ph.D. thesis.

References

- Akçay C, Reed VA, Campbell SE, Templeton CN & Beecher MD (2010). Indirect reciprocity: song sparrows distrust aggressive neighbours based on eavesdropping. *Animal Behaviour* 80: 1041–1047
- Alexander RD (1987). *The Biology of Moral Systems*. Aldine de Gruyter, New York, USA
- Ben-Porath E (2003). Communication in repeated games with costly monitoring. *Games and Economic Behavior* 44: 227–250
- Bolton GE, Katok E & Ockenfels A (2004). How effective are electronic reputation mechanisms? An experimental investigation. *Management Science* 50: 1587–1602
- Bshary R & Grutter AS (2006). Image scoring and cooperation in a cleaner fish mutualism. *Nature* 441: 975–978
- Dunbar R (1998). *Grooming, Gossip, and the Evolution of Language*. Harvard University Press, Cambridge, USA
- Hardin G (1968). The tragedy of the commons. *Science* 162: 1243–1248
- Miyagawa E, Miyahara Y & Sekiguchi T (2008). The folk theorem for repeated games with observation costs. *Journal of Economic Theory* 139: 192–221
- Nakamaru M & Kawata M (2004). Evolution of rumours that discriminate lying defectors. *Evolutionary Ecology Research* 6: 261–283
- Nowak MA (2006). Five rules for the evolution of cooperation. *Science* 314: 1560–1563
- Nowak MA & Sigmund K (1998). Evolution of indirect reciprocity by image scoring. *Nature* 393: 573–577
- Nowak MA & Sigmund K (1998). The dynamics of indirect reciprocity. *Journal of Theoretical Biology* 194: 561–574
- Nowak MA & Sigmund K (2005). Evolution of indirect reciprocity. *Nature* 437: 1291–1298
- Ostrom E (1990). *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press, Cambridge, USA
- Sommerfeld RD, Krambeck HJ & Milinski M (2008). Multiple gossip statements and their effect on reputation and trustworthiness. *Proceedings of the Royal Society Series B: Biological Sciences* 275: 2529–2536
- Sommerfeld RD, Krambeck HJ, Semmann D & Milinski M (2007). Gossip as an alternative for direct observation in games of indirect reciprocity. *Proceedings of the National Academy of Sciences of the USA* 104: 17435–17440